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APPLICATION FOR PATENT

MULTI-STATE NON-VOLATILE INTEGRATED CIRCUIT MEMORY SYSTEMS THAT EMPLOY DIELECTRIC STORAGE ELEMENTS

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FIELD OF THE INVENTION

This invention relates most specifically to non-volatile flash EEPROM (Electrically Erasable and Programmable Read Only Memory) cell arrays of a type using dielectric material charge storage elements.

BACKGROUND

There are many commercially successful non-volatile memory products being used today, particularly in the form of small cards, where the memory cells have conductive floating gates, commonly of doped polysilicon material, on which an electron charge is stored to a level of the data state being stored. A common form of such memory cells has a "split-channel" between source and drain diffusions. The floating gate of the cell is positioned over one portion of the channel and the word line (also referred to as a control gate) is positioned over the other channel portion as well as the floating gate. This effectively forms a cell with two transistors in series, one (the memory transistor) with a combination of the amount of charge on the floating gate and the voltage on the word line controlling the amount of current that can flow through its portion of the channel, and the other (the select transistor) having the word line alone serving as its gate. The word line extends over a row of floating gates. Examples of such cells, their uses in memory systems and methods of manufacturing them are given in United States patents nos. 5,070,032, 5,095,344, 5,315,541, 5,343,063, and 5,661,053, and in co-pending United States patent application serial no. 09/239,073, filed January 27, 1999, which patents and application are incorporated herein by this reference.

A modification of this split-channel flash EEPROM cell adds a steering gate positioned between the floating gate and the word line. Each steering gate of an array extends over one column of floating gates, perpendicular to the word line. The effect is relieve the word line from having to perform two functions at the same time when reading or programming a selected cell. Those two functions are (1) to serve as a gate of a select transistor, thus requiring a proper voltage to turn the select transistor on and off, and (2) to drive the voltage of the floating gate to a desired level through an electric field (capacitive) coupling between the word line and the floating gate. It is often difficult to perform both of these functions in an optimum manner with a single voltage. With the addition of the steering gate, the word line need only perform function (1), while the added steering gate performs function (2). Further, such cells may operate with source side programming, having an advantage of lower programming currents and/or voltages. The use of steering gates in a flash EEPROM array is described in United States patents nos. 5,313,421, 5,712,180, and 6,222,762, which patents are incorporated herein by this reference.

There are various programming techniques for injecting electrons from the substrate onto the floating gate through the gate dielectric. The most common programming mechanisms are described in a book edited by Brown and Brewer, “Nonvolatile Semiconductor Memory Technology,” IEEE Press, section 1.2, pages 9-25 (1998), which section is incorporated herein by this reference. One technique, termed “Fowler-Nordheim tunneling” (section 1.2.1), causes electrons to tunnel through the floating gate dielectric under the influence of a high field that is established thereacross by a voltage difference between the control gate and the substrate channel. Another technique, termed channel “hot-electron injection” (section 1.2.3), injects electrons from the cell’s channel into a region of the floating gate adjacent the cell’s drain. Yet another technique, termed “source side injection” (section 1.2.4), controls the substrate surface electrical potential along the length of the memory cell channel in a manner to create conditions for electron injection in a region of the channel away from the drain. Source side injection is also described in an article by Kamiya et al., “EPROM Cell with High Gate Injection Efficiency,” *IEDM Technical Digest*, 1982, pages 741-744, and in United States patents no. 4,622,656 and 5,313,421, which article and patents are incorporated herein by this reference.

Two techniques for removing charge from floating gates to erase memory cells are used in both of the two types of memory cell arrays described above. One is to erase to the substrate by applying appropriate voltages to the source, drain, substrate and other gate(s) that cause electrons to tunnel through a portion of a dielectric layer between the floating gate and the substrate.

The other erase technique transfers electrons from the floating gate to another gate through a tunnel dielectric layer positioned between them. In the first type of cell described above, a third gate is provided for that purpose. In the second type of cell described above, which already has three gates because of the use of a steering gate, the floating gate is erased to the word line, without the necessity to add a fourth gate. Although this later technique adds back a second function to be performed by the word line, these functions are performed at different times, thus avoiding the necessity of making compromises to accommodate the two functions.

It is continuously desired to increase the amount of digital data that can be stored in a given area of a silicon substrate, in order to increase the storage capacity of a given size memory card and other types packages, or to both increase capacity and decrease size. One way to increase the storage density of data is to store more than one bit of data per memory cell. This is accomplished by dividing a window of a floating gate charge level voltage range into more than two states. The use of four such states allows each cell to store two bits of data, a cell with sixteen states stores four bits of data, and so on. A multiple state flash EEPROM structure and operation is described in United States patents nos. 5,043,940 and 5,172,338, which patents are incorporated herein by this reference.

Increased data density can also be achieved by reducing the physical size of the memory cells and/or of the overall array. Shrinking the size of integrated circuits is commonly performed for all types of circuits as processing techniques improve over time to permit implementing smaller feature sizes. But since there are limits of how far a given circuit layout can be shrunk by scaling through simple demagnification, efforts are so directed toward redesigning cells so that one or more features takes up less area.

In addition, different designs of memory cells have been implemented in order to further increase data storage density. An example is a dual floating gate memory cell, which can also be operated with the storage of multiple states on each floating gate.

In this type of cell, two floating gates are included over its channel between source and drain diffusions with a select transistor in between them. A steering gate is included along each column of floating gates and a word line is provided thereover along each row of floating gates. When accessing a given floating gate for reading or programming, the steering gate over the other floating gate of the cell containing the floating gate of interest is raised sufficiently high to turn on the channel under the other floating gate no matter what charge level exists on it. This effectively eliminates the other floating gate as a factor in reading or programming the floating gate of interest in the same memory cell. For example, the amount of current flowing through the cell, which can be used to read its state, is then a function of the amount of charge on the floating gate of interest but not of the other floating gate in the same cell. An example of this cell array architecture, its manufacture and operating techniques are described in United States patent no. 5,712,180 (Figures 9+), which patent is incorporated herein by this reference (hereinafter referred to as the "Dual Storage Element Cell").

Another type of memory cell useful in flash EEPROM systems utilizes a non-conductive dielectric material in place of a conductive floating gate to store charge in a non-volatile manner. Such a cell is described in an article by Chan *et al.*, "A True Single-Transistor Oxide-Nitride-Oxide EEPROM Device," *IEEE Electron Device Letters*, Vol. EDL-8, No. 3, March 1987, pp. 93-95. A triple layer dielectric formed of silicon oxide, silicon nitride and silicon oxide ("ONO") is sandwiched between a conductive control gate and a surface of a semi-conductive substrate above the memory cell channel. The cell is programmed by injecting electrons from the cell channel into the nitride, where they are trapped and stored in a limited region. This stored charge then changes the threshold voltage of a portion of the channel of the cell in a manner that is detectable. The cell is erased by injecting hot holes into the nitride. See also Nozaki *et al.*, "A 1-Mb EEPROM with MONOS Memory Cell for Semiconductor Disk Application," *IEEE Journal of Solid-State Circuits*, Vol. 26, No. 4, April 1991, pp. 497-501, which describes a similar cell in a split-gate configuration where a doped polysilicon gate extends over a portion of the memory cell channel to form a separate select transistor. The foregoing two articles are incorporated herein by this reference. The programming techniques mentioned above, by reference to section 1.2 of the book edited by Brown and Brewer, are also described in that section to be applicable to dielectric charge-trapping devices.

United States patent no. 5,851,881, incorporated herein by this reference, describes the use of two storage elements positioned adjacent each other over the channel of the memory cell, one being such a dielectric gate and the other a conductive floating gate. Two bits of data are stored, one in the dielectric and the other in the floating gate. The memory cell is programmed into one of four different threshold level combinations, representing one of four storage states, by programming each of the two gates into one of two different charge level ranges.

Another approach to storing two bits in each cell has been described by Eitan *et al.*, "NROM: A Novel Localized Trapping, 2-Bit Nonvolatile Memory Cell," *IEEE Electron Device Letters*, vol. 21, no. 11, November 2000, pp. 543-545. An ONO dielectric layer extends across the channel between source and drain diffusions. The charge for one data bit is localized in the dielectric layer adjacent to the drain, and the charge for the other data bit localized in the dielectric layer adjacent to the source. Multi-state data storage is obtained by separately reading binary states of the spatially separated charge storage regions within the dielectric.

SUMMARY OF THE INVENTION

The present invention includes two primary aspects that may either be implemented together or separately. One primary aspect is directed to novel non-volatile memory cell structures that use dielectric charge storage elements rather than conductive floating gates. The other primary aspect is directed to the storage of charge in one of more than two detectable levels at one or more limited, contained regions across a dielectric charge storage element over a channel of a memory cell transistor. More than one bit of data is thereby stored in a single localized region of the dielectric over a portion of the channel. Two or more such independently programmable charge storage regions, spaced apart from each other along the length of the channel, may be provided in each memory cell of an array of such cells, wherein more than one bit of data is stored in each such region.

This invention can be implemented in a number of prior flash memory systems, such as those described above in the Background. Where a prior memory cell array utilizes conductive floating gates as storage elements, charge trapping dielectric material is substituted for the floating gates. The methods of making and operating such non-volatile memory systems with dielectric storage elements are quite similar to their conductive floating gate counterparts. Since charge does not move across a dielectric storage material, the dielectric may usually extend over most other areas of a memory cell array, across multiple rows and columns of memory cells. Where the memory cell includes a select transistor, however, gate dielectric is substituted within the select transistor for the electron storage material.

Two or more electron storage elements can be provided within the storage dielectric of each memory cell that has a gate structure allowing independent control of the electric potential across the substrate surface in respective two or more portions along the length of the memory cell channel. In the preferred implementations of the present invention, only one charge storage region is maintained within each such storage element. The enlargement or movement of a region of the dielectric into which electrons are injected, which can occur as the number of erase/programming cycles increases, thus does not affect an adjacent region within the same memory cell. This increases the number of erase/programming cycles that the memory can endure, thus increasing its effective life. This also makes it practical to store more than two memory states within each charge region since increased voltages, which are usually necessary to operate an enlarged window of charge that includes more than two charge levels defining multi-state storage, can also contribute to such enlargement or movement of the storage regions.

In a particular example, the Dual Storage Element Cell described above in the Background has charge-storing dielectric substituted for each of the two floating gates of the memory cells. This dielectric is sandwiched between conductive steering gates and the substrate to form two functionally separate charge storage elements over channels of the memory cells between their sources and drains. One region of charge is stored in each of these two storage elements, which lie along the length of the cell channels on opposite sides of the select transistors. The level of charge in a region affects the threshold level of the portion of the length of the cell channel beneath that region. Two or more such charge levels, and thus two or more different threshold levels, are defined for programming into each of the two charge storage regions of each memory cell. Programming and reading of a selected one of the two charge storage regions of an addressed cell is accomplished in the same manner as in the dual floating gate systems, by turning on the select transistor and driving the other channel portion strongly conductive. This renders the selected charge storage region of the addressed cell responsive to voltages placed on its source, drain and gates. Specific examples of Dual Storage Element Cell arrays in which the charge storage dielectric may be substituted for floating gates are given in United States patents nos. 6,091,633, 6,103,573 and 6,151,248, and in pending applications serial no. 09/667,344, filed September 22, 2000, by Yuan *et al.*, entitled "Non-volatile Memory Cell Array having Discontinuous Source and Drain Diffusions Contacted by Continuous Bit Line Conductors and Methods of Forming," serial no. 09/925,134, filed August 8, 2001, by Harari *et al.*, entitled "Non-Volatile Memory Cells Utilizing Substrate Trenches," and serial no. 09/925,102, filed August 8, 2001, by Yuan *et al.*, entitled "Scalable Self-Aligned Dual Floating Gate Memory Cell Array and Methods of Forming the Array," which patents and patent applications are incorporated herein in their entirety by this reference.

Additional aspects, advantages and features of the present invention are included in the following description of its exemplary embodiments, which description should be read in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a plan view of a first example of an array of memory cells;

Figures 2A and 2B are cross-sectional views of the array of Figure 1, taken at respective sections I-I and II-II;

Figure 3 is an enlarged view of the section of Figure 2A, showing one memory cell, plus exemplary threshold voltage characteristics across that cell;

Figure 4 is a set of exemplary current-voltage characteristic curves for the memory cell of Figure 3 operated in four states;

Figure 5 is an equivalent electrical circuit of the memory cell shown in Figure 3, plus schematic representations of some operating elements;

Figures 6A and 6B illustrate two different specific dielectric material configurations that may be used in memory cells for trapping charge;

Figure 7 shows a plan view of a second example of an array of memory cells;

Figures 8A and 8B are cross-sectional views of the array of Figure 7, taken at respective sections III-III and IV-IV;

Figure 9 is an enlarged view of the section of Figure 8A, showing one memory cell, plus exemplary threshold voltage characteristics across that cell;

Figure 10 shows a plan view of a third example of an array of memory cells;

Figures 11A and 11B are cross-sectional views of the array of Figure 10, taken at respective sections V-V and VI-VI;

Figure 12 is an enlarged view of the section of Figure 11A, showing one memory cell, plus exemplary threshold voltage characteristics across that cell;

Figure 13 is a section that shows a modification of the memory cells shown in Figure 11A; and

Figure 14 illustrates in block diagram form a flash EEPROM system in which the memory cell arrays may be implemented.

DESCRIPTION OF EXEMPLARY EMBODIMENTS

Several specific memory cell configurations are described with respect to the drawings. In each of them, charge is stored in at least one region of a charge trapping dielectric that is positioned between a conductive gate and the substrate. These memory cell examples may be operated either in a binary mode, where one bit of data is stored in each charge region, or in a multi-state mode, where more than one bit of data is stored in each region.

First Memory Cell Example (Figures 1-6)

A few cells of a two-dimensional array of cells is illustrated in Figure 1 in plan view, with orthogonal sections shown in Figures 2A and 2B. Elongated, parallel source and drain diffusions 103, 104 and 105 are formed in a surface 101 of a semiconductor substrate 100, with their lengths extending in the y-direction and are spaced apart in the x-direction. A dielectric layer 107 including a charge storage material is formed on the substrate surface 101. Elongated, parallel conductive control gates 109, 110 and 111 have lengths extending in the x-direction and are spaced apart in the y-direction. These gates can be made from doped polysilicon material, as is typical.

The charge storage elements of this simple structure (which is one of its advantages) are the areas of the dielectric layer 107 between the source and drain diffusions 103 – 105 and sandwiched between the control gates 109 – 111 and the substrate surface 101. These storage element areas are marked with cross-hatching in Figure 1. The charge trapping material needs to be positioned only in these regions in order to form operable memory cells but may be extended over any other portions of the structure that is convenient, including over the entire memory cell array.

This memory cell array may be formed by standard processing techniques, particularly those developed for making flash EEPROM arrays of the type utilizing a floating gate. The major processing steps include forming an ion implant mask on the substrate surface through which ions are them implanted into the source and drain regions 103 – 105. This mask is then removed and the dielectric layer 107 is formed over the entire array. A layer of conductive material, such as doped polysilicon or polycide, is then deposited over the dielectric 107, an etch mask formed on its top surface and the polysilicon is then etched through the mask to leave the control gates 109 – 111. In the case of polysilicon, these control gates are doped in order to make them conductive by either initially depositing the polysilicon in a doped form or subsequently doping it by implanting ions before it is separated into the elongated strips 109 – 111. When the polysilicon is etched, the layer 107 in the regions being etched may also be removed, since those regions are unnecessary to the operation of the memory, to leave strips of the dielectric layer 107 under the control gates 109 – 111. Finally, another implant may be made into the substrate between the control gate strips 109 – 111, using the control gates as a mask, in order to increase the electrical isolation between adjacent rows of cells.

The programming and charge retention of such an array is illustrated in Figure 3, where a portion of Figure 2A including a single memory cell is enlarged. Programming is accomplished by the channel hot-electron injection technique described above in the Background. When appropriate voltages are placed on the substrate 100, source 104, drain 105 and control gate 110, electrons are accelerated within the cell channel from the source toward the drain sufficiently to be injected into a region 115 within the dielectric layer 107 adjacent the drain 105 and retained there. The actual programming voltages applied depend upon details of the array structure but the following are exemplary: Substrate 100: 0 volts; source 104: 0 volts; drain 105: 5 volts; and control gate 110: 8 volts.

The preferred programming technique follows that of flash EEPROMs with conductive floating gates, as described in references discussed above in the Background. Simultaneous pulses of these programming voltages are periodically applied to a number of cells in parallel and the programmed states of the cells are read in between programming pulses. When an individual cell reaches its programmed level, application of programming pulses to that cell is terminated. It will be noted that the source and drain diffusions are shared between cells in adjacent columns, and are operated in a virtual ground mode that is widely used in the operation of floating gate memory arrays.

The length of the channel of the memory cell of Figure 3 is noted to have two components, "L1" for the portion of the length outside of the charge storage region 115, and "L2" for the portion of the length under the region 115. A curve 117 illustrates the threshold voltage (V_T) characteristics of the channel. The curve is flat along the channel length segment L1 at a level depending upon any threshold altering implant that may have been made in the substrate surface 101 and the impact of any prior channel erase operations (described hereinafter). The charge stored in the region 115 does not affect the threshold characteristics in the L1 segment. But in the L2 channel segment, the threshold is significantly affected by the stored charge, and, as in the floating gate counterpart systems, is the characteristic that is measured to determine the storage state of the cell.

Programming by Fowler-Nordheim tunneling through the layer of oxide formed on the channel region has its limitations. It can usually be used in only some specific memory array configurations, such as NAND and AND configurations. It is not practical to program this first example, or either of the second or third memory cell array examples described hereinafter, by this technique. But if programmed in this manner, the storage region within the dielectric 107 would extend substantially uniformly across the entire channel length (L1 + L2) instead of being confined to the region 115.

Each cell may be operated in binary, to store one bit of data, by detecting whether V_T is above or below one predetermined threshold level. But according to one primary aspect of the present invention, more than one bit of data may be stored in each cell by operating it to distinguish between more than two levels or ranges of V_T that are separated by more than two predetermined threshold levels. A window of threshold levels in the L2 segment is shown in Figure 3 to be divided into four states 0 – 3, as an example, which will store two bits per cell. More than four levels may alternatively be designated in order to store more than two bits per storage element. Exemplary current-voltage characteristics are shown in Figure 4 for the cell of Figure 3 in each of its four storage states as a result of an appropriate amount of charge being stored in the dielectric region 115. The quantity V_{CG} along the x-axis of Figure 4 is the voltage on the control gate 110 of the cell, and the quantity I_{CELL} on the y-axis is the current through the channel of the cell.

The memory cell shown in Figure 3 is effectively a split-channel cell because the charge storage region 115 extends across only a portion of the channel. An electrical equivalent circuit of the cell is shown in Figure 5, two transistors Q1 and Q2 being connected in series between adjacent source and drain diffusions 104 and 105 (bit lines). The transistor Q1 must be rendered conductive during programming or reading by providing a sufficient combination of voltages on the cell's elements. During read, a voltage source 121 (V_{CG}) is connected to the control gate 110 (word line), a voltage source 125 (V_S) to the diffusion 104 and a voltage source 127 (V_D) to the diffusion 105.

The cell of Figure 3 can be read in the same manner as a cell having a conductive floating gate. There are two general ways. The control gate voltage V_{CG} may be held fixed and the current through the cell (I_{CELL}) measured by a sense amplifier circuit 129 as an indication of the storage state of the cell. The actual voltages applied depend upon details of the array structure but the following are exemplary: Substrate 100: 0 volts; source 104: 0 volts; drain 105: 1 volts; and control gate 110: 3-5 volts. Alternatively, the control gate voltage V_{CG} may be varied and its value noted when the value of the cell current is determined by the sense amplifier 129 to cross a fixed threshold. That voltage value gives an indication of the storage state of the cell. This example utilizes "forward" reading, since the drain during programming is also the drain during reading. Alternatively, the reading may be performed in a "reverse" mode, where the drain and source during programming are reversed during reading.

The diagram of Figure 5 also contains the components used to program the cell, except that the sense amplifier 129 is typically not connected during programming. The voltage sources 121, 125 and 127 are connected as shown in Figure 5 during programming but the values of the voltages supplied are different. A number of cells along at least one word line may be erased together by applying appropriate voltages to cause electrons to move from the dielectric charge trapping regions to the substrate. An example set of erase voltages is as follows: Substrate 100: 0 volts; source 104: floating; drain 105: 5 volts; and control gate 110: -8 volts.

Figure 6 illustrates two exemplary structures for the charge storage dielectric layer 107 that may be used in all of the memory cell examples described herein. The first (Figure 6A) includes a layer 135 of silicon oxide (SiO_2), commonly just called "oxide," grown on the substrate surface 101, followed by a layer 137 of silicon nitride (Si_3N_4), commonly just called "nitride," being deposited over the layer 135. A layer 139 of oxide is then grown on the nitride layer 137 or deposited on it, or a combination of the two. This oxide-nitride-oxide configuration is known as "ONO." Electrons are trapped and stored in the nitride layer 137. Exemplary thicknesses of these layers are as follows: layer 135: 50 Angstroms; layer 137: 70 Angstroms; and layer 139: 100 Angstroms. The layer of conductive material from which the control gates are formed is then deposited on the ONO layer.

The second structure, shown in Figure 6B, uses a tailored layer 141 of silicon rich silicon dioxide to trap and store electrons. Such material is described in the following two articles, which articles are incorporated herein in their entirety by this reference: DiMaria *et al.*, "Electrically-alterable read-only-memory using Si-rich $SI0_2$ injectors and a floating polycrystalline silicon storage layer," *J. Appl. Phys.* 52(7), July 1981, pp. 4825-4842; Hori *et al.*, "A MOSFET with Si-implanted Gate-$Si0_2$ Insulator for Nonvolatile Memory Applications," IEDM 92, April 1992, pp. 469-472. As an example, the thickness of the layer 141 can be about 500 Angstroms.

Second Memory Cell Example

Another example memory array is illustrated in Figures 7-9, which differs from the first example by the use of two sets of orthogonally positioned conductive gates instead of just one set. Figure 7 shows a few cells of the array in plan view and Figures 8A and 8B are cross-sectional views in two orthogonal directions. Parallel source and drain diffusions 151, 152 and 153, formed in a surface 164 of a substrate 163, are elongated in the y-direction across the array and spaced apart in the x-direction. Conductive control gates 155, 156 and 157, which may be referred to as steering gates, are also elongated in the y-direction and spaced apart in the x-direction. These gates are positioned alongside respective diffusions 151, 152 and 153. These diffusions are spaced further apart than those of the first example in order to allow for these control gates to be positioned across the memory cell channels. A second set of conductive control gates 159, 160 and 161, which form the word lines of the array, are elongated in the x-direction and spaced apart in the y-direction. The conductive gates are typically formed of doped polysilicon but may alternatively be formed of other low resistance materials.

Referring to the sectional views of Figures 8A and 8B, a layer of charge storing dielectric 165 is formed over the substrate surface 164 of the array. This dielectric can be one of the two specific dielectrics described above with respect to Figures 6A-B. Another dielectric layer 167 is formed between the two sets of conductive gates where they cross each other. This layer is made to be relatively thick in order to sustain the potential voltage differences between the two sets of gates, such as a 250 Angstroms thick oxide.

It will be noted from Figure 8A, and the enlarged sectional view of one memory cell thereof in Figure 9, that the length of the individual memory cell channels is divided into two portions that are field coupled with different ones of the two sets of control gates. The word line 160 lies over the left approximately one-half of the channel length and the control gate 157 over the other. The charge storing dielectric 165 is sandwiched between the substrate surface 164 and these gates. A primary difference in operation of this array from that of the first example is that charge may be stored in two spatially separated regions 171 and 173 within the layer 165, and each of these regions may be individually programmed and read independently of the other. Programming by source side injection is preferred, which causes the charge storage region 171 to be located adjacent an interior edge of the gate 160 and the charge storage region 173 adjacent an interior edge of the gate 157. However, if programmed by channel hot-electron injection, electrons are stored in regions 172 and 174 within the layer 165 instead of in the regions 171 and 173. The regions 172 and 174 are adjacent respective ones of the cell diffusions 152 and 153.

This example cell effectively contains two charge storage elements over its channel between adjacent source and drain regions 152 and 153, one under the conductive gate 160 and the other under the conductive gate 157. The dielectric layer

165 may be limited to these areas or, as is usually more convenient, extended over more of the array. Figures 7-9 show the charge storage layer 165 extending over the entire array.

A curve 175 of Figure 9 illustrates the varying threshold voltage characteristics (V_T) across the cell's channel, when programmed in the regions 171 and 173 by source side injection. The amount of charge stored in the region 171 imparts a V_T value 177 of the threshold under it, and the amount of charge stored in the region 173 imparts a V_T value 179 of the threshold under it. Each of the threshold values 177 and 179 may be maintained in one of two storage states, where a single breakpoint threshold value is set between the states. Two bits of data are stored in each cell if this is done. Alternatively, each of the values 177 and 179 may be operated with more than two levels, as shown in Figure 3 for the first example array. If each of the levels 177 and 179 is operated in four states, as shown in Figure 3, a total of four bits of data are stored in each memory cell. Of course, if one or both portions of the channel are operated in more than four levels, more than four bits of data are stored in each cell. Also, if the cell is programmed by channel hot-electron injection instead of source side injection, the curve 175 is modified by the levels 177 and 179 being moved apart to positions under the charge storage regions 172 and 174.

Each of the threshold values 177 and 179 is preferably programmed and read independently of one another. One segment of the cell is turned on hard, thus eliminating any effect of its programmed threshold level, while the other is being programmed or read. Although the specific voltages applied to the array will depend upon its specific structure, the following are approximate voltages that might be used for programming the cell of Figure 9 by channel hot-electron injection:

Programming the left segment, threshold value 177: Substrate 163: 0 volts; source 153: $V_S = 0$ volts; drain 152: $V_D = 5$ volts; control gate 157: $V_{SG} = 8$ volts; and word line 160: $V_{WL} = 10$ volts.

Programming the right segment, threshold value 179: Substrate 163: 0 volts; source 152: $V_S = 0$ volts; drain 153: $V_D = 5$ volts; control gate 157: $V_{SG} = 8$ volts; and word line 160: $V_{WL} = 10$ volts.

Programming is also preferably accomplished in this example by alternately pulsing a plurality of cells with these voltages in parallel and verifying their programmed states by reading them, the programming being terminated on a cell-by-cell basis after reaching the desired level, as done with floating gate flash memory gate arrays.

Exemplary reading voltages for the cell of Figure 9, when programmed in the manner described above, are as follows:

Reading forward the left segment, threshold value 177 by sensing the value of the cell current I_{CELL} at fixed voltages: Substrate 163: 0 volts; source 153: $V_S = 0$ volts; drain 152: $V_D = 1$ volt; control gate 157: $V_{SG} = 8$ volts; and word line 160: $V_{WL} = 6$ volts.

Reading forward the right segment, threshold value 179 by sensing the value of the cell current I_{CELL} at fixed voltages: Substrate 163: 0 volts; source 152: $V_S = 0$ volts; drain 153: $V_D = 1$ volt; control gate 157: $V_{SG} = 6$ volts; and word line 160: $V_{WL} = 8$ volts.

Erasing of the memory cells is accomplished in this and the other two examples by the injection of holes into their charge trapping layers. These holes neutralize the negative charge of the electrons that were injected into the charge-trapping layer during a programming operation. It is the layer 165 in this second example (Figures 7 - 9) that receives the electrons during programming and the holes during erasing. There are two specific erasing techniques. In one, the holes are injected into a charge storage portion of the layer 165 from the silicon substrate by tunneling through an oxide portion of that layer that is in contact with the substrate surface, termed a "channel erase." To bring this about, a negative potential is applied to the word line with respect to the substrate, with the drain and source either being grounded or left floating. In the other technique, the holes are injected into the layer 165 from a region of the substrate near the drain or the source. In this second approach, referring to Figures 8 and 9, a combination of a negative voltage on both the word lines 159 - 161 and steering gates 155 - 157, and a positive voltage on the drains and sources 151-153, are applied. (In the cell shown in Figure 3 for the first example previously described, a positive voltage is applied to the drain 105, the source 104 is left floating, and a negative voltage is applied to the word line 110.)

When cells have been programmed by source side injection, the channel erase technique is preferred. When programmed by the hot-electron injection technique, either of these two erasing techniques can be used. But when cells have been programmed by hot-electron injection, the channel erase has a disadvantage of tunneling holes across the entire channel, the result being an over erase of a portion of the charge trapping layer that does not contain electrons trapped by prior programming. This can cause the flat zero portions of the curve 175 (Figure 9) across the cell channel to be lowered to negative threshold values.

To simultaneously erase a plurality of cells in a block of cells in this second example, the following voltages are simultaneously applied to individual cells: Substrate 163: 0 volts; source 152: V_S = 5 volts; drain 153: V_D = 5 volts; control gate 157: V_{SG} = -8 volts; and word line 160: V_{WL} = -8 volts. These voltages implement the second erase approach described above.

The memory cell array of Figures 7-9 may also be formed by standard processing techniques, particularly those developed for making flash EEPROM arrays of the type utilizing a floating gate. In one example process, the layer 165 is first formed over the entire substrate area of the memory cell array. A first layer of polysilicon is then deposited over this area and etched through an appropriate mask to leave the control gates 155 – 157. The layer 165 in between the control gates 155 – 157 is removed as part of this etching process, in one example. The source and drain regions 151, 152 and 153 are then implanted through a mask formed by the control gates and other temporary masking material (not shown), thus being self-aligned with one edge of the control gates 155 – 157. The layer 165 is then formed on the substrate surface 164 in between the control gates 155 – 157 and simultaneously over the top and sides of the control gates 155 – 157. This is a continuous layer of ONO (Figure 6A) or silicon rich oxide (Figure 6B). The layer 167 shown in Figures 8 and 9 can be part of the same layer 165 or a combination of the layer 165 and other dielectric material. Such other dielectric material can be in the form of oxide spacers (not shown) formed along the vertical walls of the control gates 155 - 157 and/or a thick oxide layer (not shown) on the top surface of the control gates 155 – 157. This top surface oxide is preferably formed by depositing the oxide on the top of the first polysilicon layer before it is separated into the gates 155 - 157. A second layer of polysilicon is then formed over this continuous layer, and is then etched into the word lines 159, 160 and 161.

It will be noted that this second example memory cell has a larger dimension in the x-direction by one resolution element than does the first example of

Figures 1-3, because of the added control (steering) gates 155 – 157. A second polysilicon layer is also required in this second example. This added structure and size, however, allows the amount of data that is stored in each cell to be doubled.

A useful modification of the cell of Figures 7-9 for some purposes replaces the electron storage layer under the control gates 155 – 157 with a thin (such as 200 Angstroms thick) gate dielectric, usually an oxide grown on the substrate surface 164. This eliminates the second electron storage region 173 but adds an independent select transistor function to each cell. Erase can then be confined to individual rows of cells.

Third Memory Cell Example

In this example, shown in Figures 10-13, an array of Dual Storage Element Cells, described above in the Background, is provided with its conductive floating gates replaced by portions of one of the dielectric charge trapping material layers described above with respect to Figures 6A – 6B. The making and operation of this array are similar to the arrays of Dual Storage Element Cells described in the patents and patent applications incorporated above into the Background and Summary.

Figures 10-12 show an array. Source and drain diffusions 185, 186 and 187 are formed in a surface 181 of a semi-conductive substrate 183, and have their lengths extending in the y-direction and are spaced apart in the x-direction. As apparent from the plan view of Figure 10, conductive steering gates 189, 190, 191, 192, 193 and 194 are oriented in the same way as the diffusions, being positioned on either side of the diffusions in the x-direction. Conductive word lines 197 – 199 are oriented with lengths extending in the x-direction and are spaced apart in the y-direction. As typical, these conductive lines are made of doped polysilicon material.

As illustrated in the sectional views of Figures 11A and 11B, the steering gates 189 – 194 are positioned over a layer 201 of charge storage material according to one of Figures 6A - 6B. After the steering gates 189 – 194 are formed over the charge trapping layer 201, strips of that layer extending in the y-direction are removed between every other of the steering gates in the x-direction. The source and drain regions 185 – 187 are implanted between the remaining regions between every other steering gate in the x-direction. An oxide layer 203 is formed over the tops and sides of the steering gates

189 – 194 to isolate those steering gates from the word lines 197 – 199, and simultaneously formed over the exposed substrate surface 181 to provide gate oxide under the word lines 197 – 199. An example thickness of the dielectric layer 203 is 200 Angstroms over the doped polysilicon steering gates 189 – 194, and 150 Angstroms on the substrate surface 181. The portions of the word line 198 shown in Figure 11A, for example, that are formed immediately over the portion of the oxide layer 203 on the substrate surface 181, serve as the select transistor gates in that row of memory cells.

Adjacent pairs of steering gates on either side of the diffusions 185 – 187 are preferably electrically connected together at a decoder for the steering gates in order to reduce the complexity of the decoder. One such pair includes steering gates 191 and 192. Such adjacent pairs of steering gates may alternatively be physically merged together by joining them over their intermediate diffusions, as described in several of the Dual Storage Element Cell patents and applications referenced above.

Individual storage elements can be defined to exist in regions of the dielectric trapping layer 201 under one of the steering gates 189 – 194 where one of the word lines 197 – 199 crosses, as shown in cross-hatching in the plan view of Figure 10. There are two such storage elements per memory cell. Each storage element can be operated in two states (binary) in order to store 1 bit per storage element. The storage elements may alternatively be operated to individually store more than two states, such as four states per storage element, in a manner similar to that described in the Dual Storage Element Cell patent no. 6,151,248. The operation of such a dielectric storage memory array is similar to what is described in that patent, one difference being the use of lower voltages on the steering gates since there are no floating gates.

With reference to Figure 12, an enlarged view of one of the memory cells of Figure 11A is given. Charge is trapped within the dielectric layer 201 in two regions 211 and 213, adjacent to each side of a select transistor gate 198' that is part of the word line 198, if programmed by the source-side injection technique. If programmed by the channel hot-electron injection technique, on the other hand, these charge regions are located adjacent the source and drain regions 186 and 187 instead. The portions of the dielectric 201 within the memory cell on either side of the select transistor gate 198' and beneath the word line 198 define the two storage elements of the cell that replace the two conductive floating gates of the Dual Storage Element Cell arrays and systems referenced above. The dielectric layer 201, however, can extend beyond these storage elements. In one form, the layer 201 is formed in strips having individual widths that extends in the x-direction between select transistors of memory cells in adjacent columns and lengths that extend in the y-direction across a large number of rows of memory cells. These strips, and the select transistor gate dielectric between them, can be self-aligned with edges of the steering gates, such as the edges of the steering gates 192 and 193 that are shown in Figure 12.

The effect of charge stored in the regions 211 and 213 of the dielectric 201 is shown by a threshold voltage curve 215 of Figure 12, similar to the other two examples described above, when programmed by source side injection. A curve portion 217 indicates a variation of the threshold voltage V_T of a portion of the memory cell channel under the charge region 211. Similarly, the effect of the charge region 213 on the channel is indicated by the portion 219 of the curve 215. Each of these regions may be operated in two states (storing one bit per cell) or more than two states (storing more than one bit per cell), as previously described above for the other examples. If programmed by channel hot-electron injection, on the other hand, the curve portions 217 and 219 are positioned further apart from each other, under the alternate locations of the charge trapped in the layer 201 that is mentioned above.

Figure 13 shows an optional modification of the memory cell shown in cross-section of Figures 11A and 12. The difference is that the select gate portion of the word line 198' extends into a groove or recess 221 in the substrate 183, with the select transistor gate dielectric 205' formed between them along the bottom and walls of the groove 221. This structure increases the length of the channel of the select transistor without taking any additional area across the substrate surface 181.

Although the gates in the foregoing structure are preferably made of doped polysilicon material, other suitable electrically conductive materials may be used in place of one or both of the polysilicon layers described. The second layer, for example, from which the word lines 197 – 199 are formed, may be a polycide material, which is polysilicon with a conductive refractive metal silicide, such as tungsten, on its top surface in order to increase its conductivity. A polycide material is usually not preferred for the first conductive layer from which the steering gates 189 – 194 are formed because an oxide grown from a polycide as an interpoly dielectric is of lower quality than that grown from polysilicon. The same considerations apply for the second memory cell example described above. For the first memory cell example, since only one layer of conductive gates is formed, those gates may be a polycide material.

Memory System Operation, in General

An example memory system in which the various aspects of the present invention may be implemented is generally illustrated in the block diagram of Figure 14. This system is most specifically directed to use of the second and third example arrays discussed above with control (steering) gates elongated in the y-direction but also has application to the first example by elimination of the circuits that connect to steering gates.

A large number of individually addressable memory cells 11 are arranged in a regular array of rows and columns, although other physical arrangements of cells are certainly possible. Bit lines, designated herein to extend along columns of the array 11 of cells, are electrically connected with a bit line decoder and driver circuit 13 through lines 15. Word lines, which are designated in this description to extend along rows of the array 11 of cells, are electrically connected through lines 17 to a word line decoder and driver circuit 19. Steering gates, which extend along columns of memory cells in the array 11, are electrically connected to a steering gate decoder and driver circuit 21 through lines 23. The steering gates and/or bit lines may be connected to their respective decoders by techniques described in a co-pending patent application by Harari *et al.* entitled "Steering Gate and Bit Line Segmentation in Non-Volatile Memories," serial no. 09/871,333, filed May 31, 2001, which application is incorporated herein by this reference. Each of the decoders 13, 19 and 21 receives memory cell addresses over a bus 25 from a memory controller 27. The decoder and driving circuits are also connected to the controller 27 over respective control and status signal lines 29, 31 and 33. Voltages applied to the steering gates and bit lines are coordinated through a bus 22 that interconnects the steering gates and bit line decoder and driver circuits 13 and 21.

The controller 27 is connectable through lines 35 to a host device (not shown). The host may be a personal computer, notebook computer, digital camera, audio player, various other hand held electronic devices, and the like. The memory system of Figure 14 will commonly be implemented in a card according to one of several existing physical and electrical standards, such as one from the PCMCIA, the CompactFlash™ Association, the MMC™ Association, and others. When in a card format, the lines 35 terminate in a connector on the card that interfaces with a complementary connector of the host device. The electrical interface of many cards follows the ATA standard, wherein the memory system appears to the host as if it was a magnetic disk drive. Other memory card interface standards also exist. Alternatively to the card format, memory systems of the type shown in Figure 14 are permanently embedded in the host device.

The decoder and driver circuits 13, 19 and 21 generate appropriate voltages in their respective lines of the array 11, as addressed over the bus 25, according to control signals in respective control and status lines 29, 31 and 33, to execute programming, reading and erasing functions. Any status signals, including voltage levels and other array parameters, are provided by the array 11 to the controller 27 over the same control and status lines 29, 31 and 33. A plurality of sense amplifiers within the circuit 13 receive current or voltage levels that are indicative of the states of addressed memory cells within the array 11, and provides the controller 27 with information about those states over lines 41 during a read operation. A large number of such sense amplifiers are usually used in order to be able to read the states of a large number of memory cells in parallel. During reading and program operations, one row of cells is typically addressed at a time through the circuits 19 for accessing in the addressed row a number of cells that are selected by the circuits 13 and 21. In one embodiment, during an erase operation, all cells in each of many rows are addressed together as a block for simultaneous erasure.

Operation of a memory system such as illustrated in Figure 14 is described in patents and pending applications identified above, and in other patents and pending applications assigned to SanDisk Corporation, assignee of the present application. Those of the cited references that describe the structure, processing or operation of a memory system using floating gates as the storage elements will be recognized as being relevant to implementing the systems using dielectric storage elements in place of the floating gates. In addition, United States patent application serial no. 09/793,370, filed February 26, 2001, describes a data programming method applied to either floating gate or dielectric storage element systems, which application is incorporated herein by this reference.

Other Memory Cell Configurations

Other configurations of memory cell arrays that use conductive floating gates may similarly be modified to replace the floating gates with charge trapping dielectric material, and then to operate each charge storage region of the array either in binary (two states) or multi-states (more than two states). For example, certain configurations described in patents and patent applications referenced above position either of the storage elements or source/drain diffusions in trenches, the trenches either being rectangular in cross-section or V-shaped. In these embodiments, the conductive storage elements can also be replaced with charge trapping dielectric material.

Conclusion

Although the various aspects of the present invention have been described with respect to specific examples thereof, it will be understood that the invention is entitled to protection within the full scope of the appended claims.